Cover: Conceptual diagram depicting shallow agricultural land-use monitoring wells and a domestic well completed in the Mississippian carbonate aquifer. Photograph on left side of cover shows a submersible pump in a monitoring well adjacent to a field of winter wheat near Huntsville, Alabama. Photograph on right side of cover is a cotton field in northern Alabama.

Shallow Ground-Water Quality in Agricultural Areas of Northern Alabama and Middle Tennessee, 2000-2001

By James A. Kingsbury

U.S. GEOLOGICAL SURVEY

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U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director

FOREWORD

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. (http://www.usgs.gov/). Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity *and* quality, even more critical to the long-term sustainability of our communities and ecosystems.
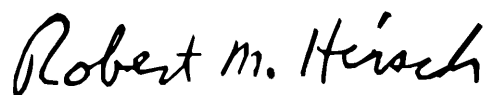
The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. (http://water.usgs.gov/nawqa/). Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues and priorities. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. (http://water.usgs.gov/nawqa/nawqamap.html). Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings. (http://water.usgs.gov/nawqa/natsyn.html).

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch

Robert M. Hirsch
Associate Director for Water

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FIGURES

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CONVERSION FACTORS, DATUMS, AND WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F = (1.8 × °C) + 32

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Water-quality units

mg/L   milligrams per liter

μg/L   micrograms per liter

μS/cm   microsiemens per centimeter

pg/kg   picogram per kilogram

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ABSTRACT

As part of the U.S. Geological Survey National Water-Quality Assessment Program, 32 monitoring wells were installed near cropland in parts of northern Alabama and Middle Tennessee to characterize the effect of row-crop agriculture on shallow ground-water quality. The wells were completed in regolith overlying carbonate bedrock. These geologic units are part of the Mississippian carbonate aquifer, a source of drinking water for domestic and municipal supply in the area. The majority of these wells were sampled in the spring of 2000 for inorganic constituents, nutrients, pesticides, and selected pesticide degradates. Land use and soil characteristics were delineated for a 1,640-foot radius buffer area around each well to relate water quality to environmental factors. A strong association among soil characteristics, land use, and hydrogeology limited the analysis of the effect of these factors on nitrate and pesticide occurrence.

Nitrate and pesticide concentrations generally were low, and no samples exceeded established drinking-water maximum contaminant levels. The maximum concentration of nitrate was about 8 milligrams per liter as nitrogen, and the median concentration was 1 milligram per liter. Nitrate concentrations were strongly correlated to dissolved-oxygen concentrations, and ratios of chloride to nitrate indicate nitrate concentrations were affected by denitrification in about a third of the samples. A pesticide or pesticide degradate was detected at concentrations greater than 0.01 microgram per liter in 91 percent of the samples. Pesticides with the highest use typically were detected most frequently and at the highest concentrations; however, glyphosate had the highest estimated use but was not detected in any samples. Fluometuron and atrazine, two high-use pesticides, were detected in 83 and 70 percent, respectively, of the samples from wells where the pesticide was applied in the buffer area. Maximum concentrations of fluometuron and atrazine were 2.13 and 1.83 micrograms per liter, respectively. Detection rates of pesticide degradates were similar to parent pesticides, and concentrations of degradates generally were comparable to or greater than the parent pesticide. Pesticide detections were correlated to dissolved-oxygen concentrations, suggesting that pesticides are most likely to be detected at high concentrations where ground-water residence time is short and the rate of recharge is fast.

Nitrate and pesticide data collected in this study were compared to data collected from similar agricultural land-use studies conducted by the National Water-Quality Assessment Program throughout the Nation. Nitrate concentrations generally were lower in this study than in samples from other agricultural areas; however, pesticides were detected more frequently in samples from wells in this study. For example, atrazine and its degradate, deethylatrazine, were detected in 62 and 47 percent, respectively, of water samples in this study but were detected in about 25 percent of the 851 wells sampled for agricultural land-use studies nationwide. In national study areas where atrazine use is greater than in the lower Tennessee River Basin, atrazine was detected in 30 percent of the water samples. Pesticides used on cotton were detected much more frequently in this study,

but many of the study areas nationwide have smaller amounts of cotton acreage than the lower Tennessee River Basin.

Similarities in nitrate concentrations and the pesticides detected frequently in this agricultural land-use study and a network of drinking-water wells in the same area completed in bedrock in the Mississippian carbonate aquifer (sampled in a previous study) indicate the aquifer is susceptible to contamination from nonpoint sources. Nitrate concentrations were not statistically different for the two well networks and were correlated to total pesticide concentrations in both networks. Although detection frequencies and maximum concentrations were higher in the land-use monitoring wells than in the drinking-water wells, the same pesticides were detected frequently, and median concentrations of these pesticides were similar. The similarity in water quality between samples from the shallow land-use and the deeper drinking-water wells is probably the result of the karst hydrology of the aquifer, which allows substantial transport of nonpoint-source contaminants from agricultural areas once water has moved through the regolith to conduits in bedrock.

INTRODUCTION

Nitrate and pesticide contamination of ground water in agricultural areas is an important issue because ground water is often the principal source of drinking water in northern Alabama and Middle Tennessee. Although local, regional, and national reconnaissance studies of nitrate and pesticides in ground water have been conducted, these studies typically have evaluated the quality of water obtained from existing domestic or public-supply wells. These types of wells commonly withdraw water from deep parts of aquifers where the effects of land use on water quality are less evident.

As part of the U.S. Geological Survey National Water-Quality Assessment (NAWQA) Program in the lower Tennessee River Basin (LTEN), a network of shallow land-use monitoring wells was installed in parts of northern Alabama and Middle Tennessee to characterize the quality of recently recharged ground water near agricultural fields (figs. 1 and 2). The data

from these shallow wells represent parts of the aquifer most affected by land-use activities at land surface and serve as a point of comparison for the effects of land use on the drinking-water resource. Wells were installed near agricultural fields in the Eastern Highland Rim, one of nine subunits (fig. 1) that generally correspond to Level III and IV ecoregion boundaries (Griffith and others, 1997; Kingsbury and others, 1999) and into which the LTEN was subdivided. These monitoring wells are nested within a network of predominantly domestic wells in the same subunit that was sampled in the summer of 1999 (Kingsbury and Shelton, 2002).

The Eastern Highland Rim is underlain by carbonate rocks of Mississippian age that make up the Mississippian carbonate aquifer, the most areally extensive and productive aquifer in the LTEN. Estimated ground-water withdrawals from the Mississippian carbonate aquifer for public and domestic supply in the Eastern Highland Rim was about 40 Mgal/d in 1995 (U.S. Geological Survey, 1997). The City of Huntsville, Alabama, is the largest ground-water user, withdrawing about 14 Mgal/d from wells that have a maximum depth of 125 ft. Ground water accounts for about 40 percent of water used in Huntsville. About 25 public water-supply systems rely on ground water from the Mississippian carbonate aquifer in the Eastern Highland Rim. About 5 Mgal/d of the total ground-water withdrawals for 1995 were for domestic use.

Purpose and Scope

This report describes the quality of shallow ground water collected in the spring of 2000 and 2001 from monitoring wells installed near agricultural areas in the Eastern Highland Rim of the LTEN study area. Soil properties, hydrogeology, and land-use data in the area near the monitoring wells are evaluated to determine the principal factors that affect the occurrence of nitrate and pesticides. The occurrence and distribution of nitrate and pesticides in the Mississippian carbonate aquifer are put into a broader context by comparing the results from other NAWQA agricultural land-use studies across the Nation. The nitrate and pesticide data in this study also are compared to data from a network of predominantly domestic wells sampled in 1999 to characterize the effect of agricultural land use on the quality of drinking water in the aquifer.
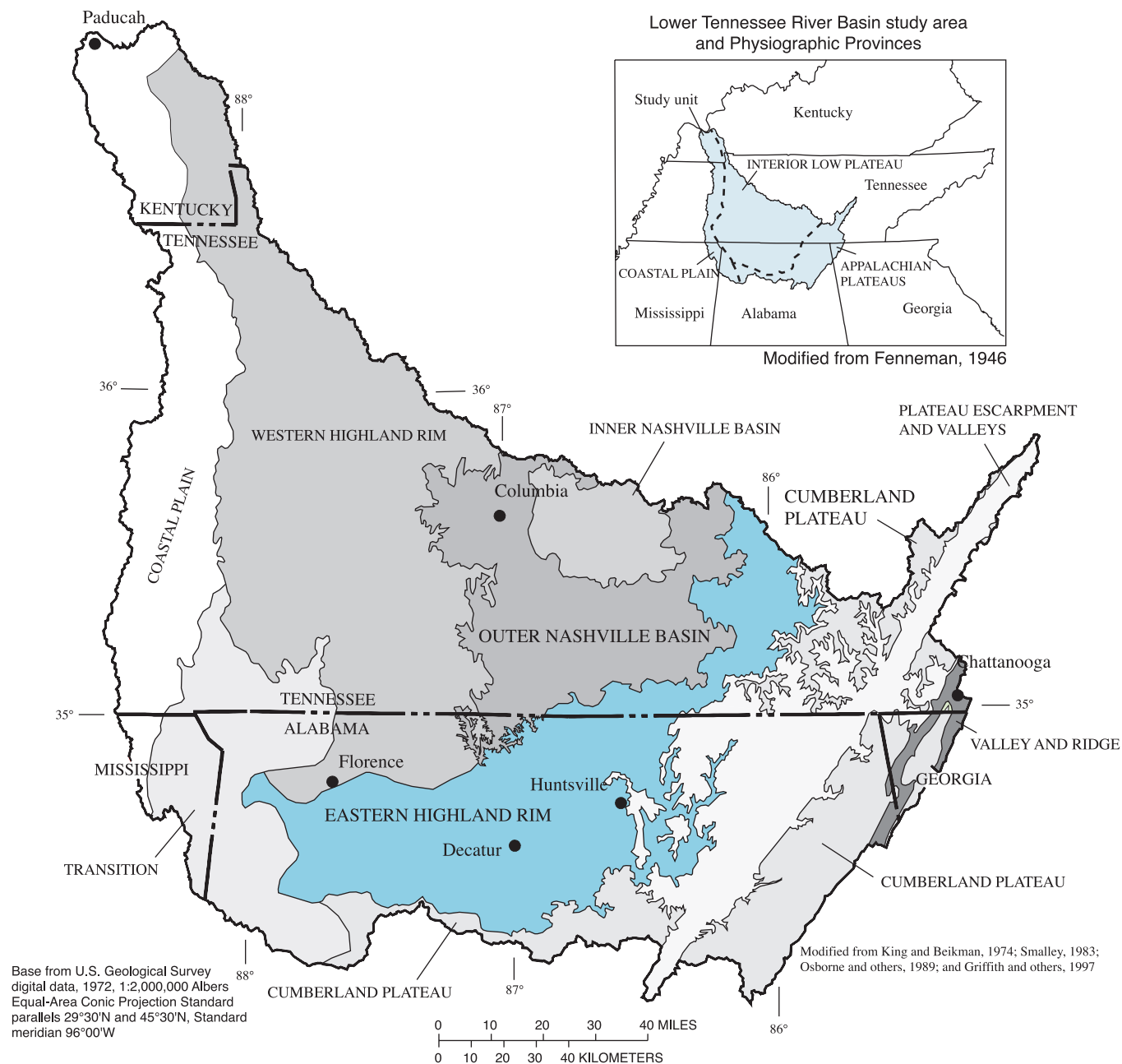
Figure 1. Location of the lower Tennessee River Basin with its delineated subunits, including the Eastern Highland Rim study area.

Acknowledgments

Figure 2. Location of wells sampled and 1992 distribution of cropland in the Eastern Highland Rim.

APPROACH

A network of 32 monitoring wells was established to characterize shallow ground-water quality in the Mississippian carbonate aquifer in agricultural areas in the Eastern Highland Rim (fig. 2). Cropland delineated from 1992 digital land-use data in the Eastern Highland Rim were combined into about 40 equal subareas from which random locations were generated using a geographic information system (GIS) based computer program (Scott, 1990). Suitable sites for monitoring wells within about a mile radius of random points generated by this program were then located. Wells were installed near agricultural fields, usually along buffer strips adjacent to fields. The direction of ground-water flow was not known, so wells were installed in locations presumed to be downgradient of the fields.

The wells installed for this study were intended for sampling water near the water table to characterize the effect of row-crop agriculture on the quality of recently recharged ground water. Thirty-two wells were drilled using hollow-stem augers and completed with 2-in.-diameter threaded polyvinyl chloride (PVC) casing. The wells were completed in regolith and were drilled in 1999 during October and November when ground-water levels typically are lowest. The top of the well screens generally were within 10 ft of the

water table. Eight of the wells had more than 10 ft of water above the screens, and 12 wells had water levels below the top of the screen at the time of sampling. Well screens were 0.01-in.-diameter slotted 10-ft-long PVC, with the exception of three wells with 5-ft-long screens. Wells ranged from 14 to 79 ft deep, with a median depth of 37.5 ft. A sand pack was placed around the well screens, and a bentonite seal was placed on top of the sand pack at least 2 ft above the top of the screen. The remainder of the annulus was grouted to land surface with a cement-bentonite mixture. Wells were developed several weeks prior to sampling, by pumping or bailing if the well did not produce enough water, typically until the turbidity was less than 10 nephelometric turbidity units.

Samples were collected and processed according to NAWQA ground-water sampling protocols (Koterba and others, 1995). Wells were purged a minimum of three casing volumes; specific conductance, dissolved oxygen, pH, and temperature were monitored until they stabilized prior to sampling. Wells that could not be pumped continuously were pumped dry, and the water level was allowed to recover to 90 percent of the pre-pumping level, at which time the wells were sampled. Samples for inorganic constituents were filtered through a disposable 0.45-μm capsule filter, and samples for cation analysis were preserved with nitric acid. Pesticide samples were filtered through a 0.7-μm disposable glass-fiber filter. Nutrient and pesticide samples were kept chilled and shipped overnight to the U.S. Geological Survey National Water-Quality Laboratory (NWQL) in Denver, Colorado. All sampling equipment was constructed of stainless steel or teflon and was cleaned with three volumes (pump line) of soapy wash, tap-water rinse, and a final rinse with de-ionized water. The aluminum pesticide filtration unit also was rinsed with pesticide-grade methanol.

Analytical Methods

Samples were analyzed using approved U.S. Geological Survey (USGS) methods at the NWQL in Denver, Colorado, and at the USGS Organic Geochemistry Research Laboratory (OGRL) in Lawrence, Kansas. Dissolved inorganic constituents were determined by atomic absorbtion, inductively coupled plasma, ion chromatography, ion specific electrode, and colorimetric methods, as described in Fishman and Friedman (1989) and Fishman (1993).

Two analytical methods were used at the NWQL (Zaugg and others, 1995; Furlong and others, 2001), and one method was used at the ORGL (Kish and others, 2000) to analyze a total of 93 pesticides and 19 pesticide degrades (appendix 1). Pesticides were extracted from samples by pumping filtered samples through solid-phase extraction columns. Extracts from these columns were subsequently analyzed by gas chromatography/mass spectrometry (GC/MS) and high-performance liquid chromatography/mass spectrometry (HPLC/MS). Minimum reporting levels (MRL) range from 0.001 to 0.193 μg/L and are based on method detection limits (MDL) for each pesticide. The MDL represents the lowest concentration at which a constituent can be identified and measured with 99 percent confidence that the concentration was greater than zero (Wershaw and others, 1987) and varies based on the performance of the method for each pesticide. Some concentrations are qualified with an "E" indicating an estimated concentration. These concentrations are estimated because they are either above or below the range in concentration of the calibration standards; the sample matrix interfered with the measurement of the analyte; surrogates added to samples indicated that the method was not performing adequately; or the analyte has systematically had low or inconsistent recoveries throughout the development and implementation of the method and concentrations always are reported as estimates (appendix 1).

Samples were analyzed by the HPLC/MS method before final approval by the USGS Office of Water Quality in April 2001. Although the analytical method did not change following approval, data analyzed before method approval are considered provisional. During initial implementation of this analytical method in 1999, a backlog of samples resulted in a number of samples exceeding the recommended 4-day holding time prior to sample extraction (Furlong and others, 2001). Samples collected from the agricultural monitoring wells in 2000 and 2001 met the recommended holding times, but samples from some of the drinking-water wells presented in this report did not. Degradation of pesticides during extended sample storage is likely, and concentrations and detection frequencies for the pesticides analyzed by this method may be biased low in the samples from the drinking-water wells. Pesticides analyzed by HPLC/MS are shown in italics in appendix 1.

Analyses of fluometuron and norflurazon degradates were conducted by GC/MS at the OGRL.

Analytical methods are described in Kish and others (2000). The MRL for these degradates is 0.05 µg/L (appendix 1). Glyphosate was analyzed by enzyme-linked immunosorbant assay at the OGRL (Lee and others, 2002) and had a MRL of 0.1 µg/L. At the time these samples were analyzed, these analytical methods also were not yet approved, so the results are considered provisional.

Quality Assurance and Quality Control

The low-level concentrations at which pesticides were analyzed in this study necessitated quality-control sampling to demonstrate that equipment cleaning, sample collection and processing, and analytical procedures were noncontaminating and to identify bias in the methods. Field quality-assurance samples made up about 30 percent of all samples analyzed and included blanks, replicates, and pesticide spikes. Data from inorganic constituent and pesticide blanks indicate that equipment cleaning procedures were adequate and that sample collection and processing procedures generally were noncontaminating. Only two pesticides were detected in a total of five blanks. Terbacil was detected in two blanks but was not present in any environmental samples. Diuron was detected at an estimated concentration of 0.01 µg/L in one blank; environmental samples associated with this blank did not contain diuron. Recoveries of spiked pesticides ranged from 5 to 245 percent for all of the pesticides analyzed, and the median recovery was 86 percent. For pesticides detected in this study, the range in recoveries was 52 to 245 percent with a median recovery of 86 percent. Recoveries of several spiked pesticides have had considerable and systematic bias with these analytical methods; deethylatrazine, aldicarb (52 percent) and its degradates, and hydroxyatrazine were biased low. Carbaryl and carbofuran (245 percent), which historically have had poor recoveries with this analytical method (Zaugg and others, 1995), were biased high in spiked samples analyzed.

Delineation of Land Use and Soil Properties Near Wells

Because the rate and direction of ground-water flow generally is not known for monitoring wells installed for the NAWQA Program, a 1,640-ft (500-m) buffer area was used for characterizing land use near monitoring wells. Based on data from other studies, Koterba (1998) concluded that a buffer area of this size likely would represent at least part of the recharge area for a well in a shallow, unconfined aquifer and should be used in NAWQA ground-water studies. High-resolution black and white aerial photographs at a 1:20,000 scale were used to delineate land use within the buffer area around each well. All of the aerial photographs, with the exception of one which was taken in 1992, were taken between 1997 and 1999 by the National Aerial Photography Program. A mylar overlay was used to delineate land-use areas. Land uses identified from aerial photographs and crops were verified by site visits. The area of each land-use type in buffer areas was determined using a planimeter. Planimeter measurements were made three times and averaged. The sum of the land-use areas was within 2 percent or less of the total buffer area measured with the planimeter for most of the wells. Differences for a few wells were as much as 5 percent because of measurement error associated with the large number and small size of land-use areas delineated. Land-use data also were delineated using the same methodology for a network of existing, predominantly domestic wells, and the relative percentages of land uses in those buffer areas were calculated by using GIS.

These land-use data were used to estimate pesticide use for the 2000 growing season in each of the buffer areas. Information about application rates was provided by local agricultural officials and also were obtained from the national pesticide use database maintained by the National Center for Food and Agricultural Policy (2002). These application rates were multiplied by the percentage of acreage typically treated and by the acreage of a given crop in the buffer areas determined from the aerial photographs.

Soil properties were characterized for the buffer areas around each well. County soil survey maps (scale 1:20,000) were used to delineate soil map units within the buffer areas. Mylar overlays with soil map unit boundaries were scanned and converted into digital coverages. The area of each map unit within the buffer was determined by GIS. Digital soil maps at a scale of 1:24,000 from the National Soil Survey Geographic (SSURGO) database (U.S. Department of Agriculture, 2001a) were available for Limestone and Madison Counties in Alabama. Soil map units in buffers around wells in these counties were delineated from these digital data. Soil attributes for map units were obtained from the National Map Unit Interpretation Record (MUIR) database (U.S. Department of

Agriculture, 2001b). Soil properties were derived for only the first soil layer because not all map units had data for deeper layers and because soil attributes for deeper layers generally were similar to the first soil layer for map units with multiple layers. Minimum, maximum, and mean values were used for soil properties that had ranges. Percentages of sand and silt are not in the MUIR database but were calculated (following Burkart and others, 1999) by subtracting the percentage of material passing through a 0.08-mm and a 50-mm sieve (sand) and the clay percentage from the 0.08-mm sieve (clay). Categorical properties, such as hydrologic group, were converted to continuous variables by using the percentage of the buffer area containing soils in a given group. Soil data were not available for one well, so that well is not included in any data analysis involving soil properties.

Statistical Methods

Several statistical tests were used in this study to evaluate relations between water-quality constituents and environmental factors that could affect constituent concentrations in ground water. The Spearman rank correlation test (Helsel and Hirsch, 1992) was used to evaluate whether nitrate and pesticide concentrations are correlated to other water-quality constituents, site characteristics, and land use. Wilcoxon rank sum tests were used to determine if constituent concentrations are significantly different for two groups of samples. For example, samples from wells with detections were compared to samples from wells without detections to determine whether environmental factors are significantly different for the two groups of wells. Partial correlation analysis (Blalock, 1972) was used to determine whether two colinear variables contribute to the variability in nitrate and pesticide concentrations, or whether one variable explains most of the variability in concentration. Partial correlation analysis determines the strength of the correlation between two variables if a third, correlated variable were to be held constant (Lowry, 2000). A significance level of 5 percent ($p < 0.05$) was used for statistical analysis of the data for this study. A common reporting level of 0.01 µg/L was used for computing detection frequencies for pesticides in this report, with the exception of those pesticides analyzed by the OGRL that did not include estimated concentrations below the MDL.

HYDROGEOLOGY

Much of the study area is underlain by the Mississippian-age Tuscumbia Limestone and Fort Payne Chert, a cherty limestone (Osborne and others, 1989). Most of the wells were completed in regolith overlying these formations. In Tennessee, the equivalent units to the Tuscumbia Limestone are the Warsaw and St. Louis Limestones. Two wells were installed in regolith overlying the Monteagle Limestone, which crops out in the southern part of the Eastern Highland Rim. The predominantly carbonate geology of these formations has resulted in the development of karst landforms such as sinkholes, caves, disappearing streams, and springs throughout much of the subunit. The regolith is a layer of residual material derived in place from the weathering of the carbonate bedrock. The regolith consists of a mixture of clay, silt, and clay-sized chert, with some chert gravel and chert interbeds. Gravel is scattered throughout the regolith but typically is more abundant and larger above the contact with bedrock where locally, bedrock cobbles or boulders may be present. Locally, these sediments are reworked and redeposited. The regolith can be as much as 100 ft thick but typically is between 30 and 60 ft thick.

The regolith and underlying bedrock are hydrologically connected, and in this report, the saturated regolith and bedrock are referred to as the Mississippian carbonate aquifer. Ground water in the aquifer typically is under water-table conditions; however, clay layers in the regolith can provide varying degrees of confinement locally. Recharge to the aquifer is largely from precipitation infiltrating and moving through the regolith. Focused recharge also occurs from surface drainage into sinkholes or losing stream reaches that intersect the aquifer.

Most of the wells were screened in parts of the aquifer that remained saturated throughout the year, but nine wells that were completed at the top of bedrock were dry during part of the year. Of these nine wells, some are well connected to ground water in bedrock, and the dry periods represent times of the year when the water level in the aquifer was below the top of bedrock (below the bottom of the well). Other wells were dry for part of the year because they may not be well connected to ground water in bedrock. These wells are analogous to wells completed in perched water-bearing zones in that they are not well connected to the water table and go dry as recharge decreases in the summer as water drains into conduits

in bedrock. Without a nearby water-level measurement in a well completed in bedrock, determining which scenario applies to a given well is difficult. Figure 3 shows a conceptual diagram of the hydrogeology of the Mississippian carbonate aquifer and hydrographs of wells that represent different hydrologic conditions in the regolith. Monthly measurements indicate that water levels fluctuated as much as 20 ft throughout the year (fig. 3) in some wells. Hydrograph A (fig. 3) represents a shallow well (well 18) screened in fine-grained material at the top of bedrock that was dry for parts of the year. Water levels rose in response to rainfall in the winter and spring and declined at about the same rate as they had risen as precipitation decreased and evapotranspiration rates increased. Hydrograph B (fig. 3) represents data from a deeper well (well 11) screened in a gravel zone that remained saturated all year. Water levels responded more slowly to rainfall in the winter and continued to decline through the beginning of February before they began to rise (fig. 3). The rate of water-level decline was slower in well 11 than in well 18, which may represent a contribution of recharge from areas with low permeability or diffuse recharge.

Specific capacities of wells installed for this study generally were low (table 1). Only four of the wells had specific capacities greater than 1 (gal/min)/ft of drawdown; more than half of the wells had specific capacities less than 0.1 (gal/min)/ft of drawdown. These low specific capacities are not surprising considering the predominance of fine-grained material in the regolith and the small diameter of the wells. Lateral movement of ground water in the regolith near these low capacity wells is probably limited, and the principal direction of ground-water flow is downward toward conduits in bedrock; therefore, recharge to these wells likely is localized. Wells intersecting gravel zones have higher specific capacities and likely have larger areas of contribution and a larger component of lateral ground-water flow than wells completed in predominantly fine-grained material in the regolith (fig. 3).

Estimated Age of Ground Water

Chlorofluorocarbons (CFCs) have been used in numerous studies to estimate the recharge age of ground water (Busenberg and Plummer, 1992). The basis of CFC age-dating is that atmospheric concentrations of three CFCs (CFC-11, CFC-12, and CFC-113) increased from about 1945 to the mid 1990s because of increases in production of these chemicals. As a result, CFC concentrations in rainfall and recharge water have had corresponding increases in concentrations until the early to mid-1990s. The model recharge date (assuming piston flow) estimated for ground-water recharge represents the time at which infiltrating precipitation (recharge) was isolated from the atmosphere and assumes no modification of CFC concentrations in ground water as a result of degradation or sorption. CFC concentrations greater than atmospheric air and water equilibrium concentrations indicate that ground water is contaminated by a local source of CFCs, and reliable recharge ages cannot be estimated. With no modification of CFC concentrations in the subsurface, all three CFCs should yield the same model recharge date.

A subset of nine wells was analyzed for CFCs to estimate the ground-water age. These nine wells were selected for CFC analysis because they could be pumped without drawing the water level down to the pump intake during sample collection, which would allow air to enter the pump. Introduction of air during sampling could contaminate the sample and affect the apparent age of ground water. Model recharge dates determined for each of the CFCs indicated contamination by CFCs locally as well as some degradation of CFCs (table 1 and appendix 2). In general, CFC-12 is the most stable of the three CFCs and usually provides the most reliable age if local contamination does not occur (Busenberg and Plummer, 1992). CFC-12 model recharge dates for the nine wells ranged from about 1969 to modern (post-1997) with most of the wells having recharge dates between 1992 and 1997 (table 1). Samples collected from wells that are hydraulically connected to the bedrock part of the aquifer likely are mixtures of water with varying residence times in the aquifer. The earlier the model recharge date in samples from these wells, the greater the proportion of "old" water. Samples with model recharge dates prior to 1997 (table 1) indicate that at least some proportion of the water in these wells has a residence time of 3 or more years. Model recharge dates for wells 25 (1969) and 33 (1978) may be overestimates because of degradation of CFCs, which can occur in ground water with low concentrations of dissolved oxygen (Plummer and Busenberg, 2000). Dissolved-oxygen concentrations were 0.4 and 4.7 mg/L, respectively, in these wells. Water from well 33 may represent a mixture of water with low dissolved-oxygen and CFC concentrations with water containing both dissolved oxygen and CFCs.

EXPLANATION

PRECIPITATION

WATER LEVEL

DIRECTION OF GROUND-
WATER FLOW
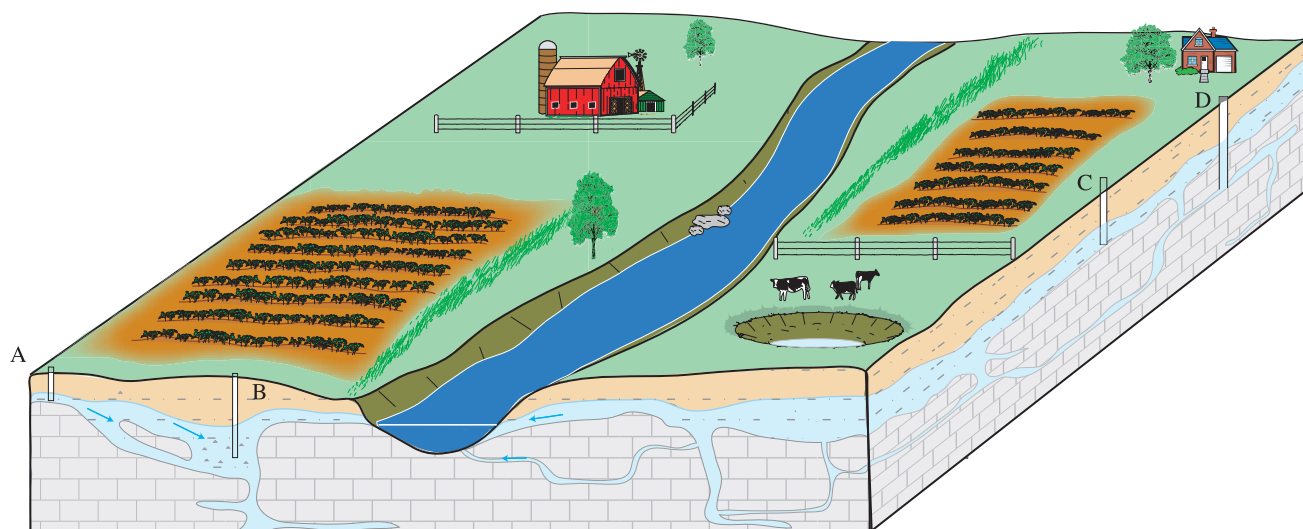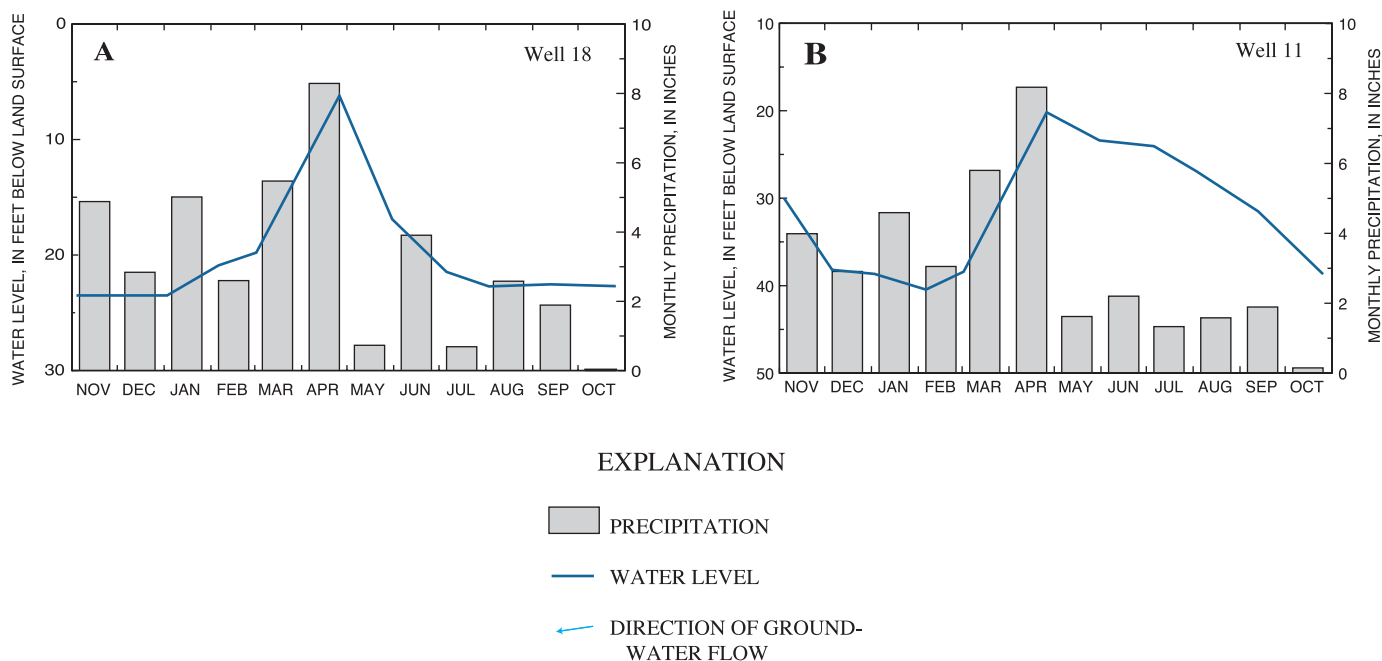
Note: Three land-use monitoring wells (A-C) and one domestic well (D) are shown. A and C represent wells that do not have a good connection with the bedrock part of the aquifer; recharge is local and the principal ground-water flow direction is toward conduits in bedrock. B represents a well in good connection with the bedrock part of the aquifer and has a larger contributing area than wells A and C. The domestic well D is completed in bedrock and has a larger contributing area than the monitoring wells.

Figure 3. Conceptual model of ground-water flow in the regolith and bedrock of the Mississippian carbonate aquifer and monthly water levels for two wells that show different responses to precipitation.